THE COSMOGONY OF COMETS.[1]

By T. J. J. See.

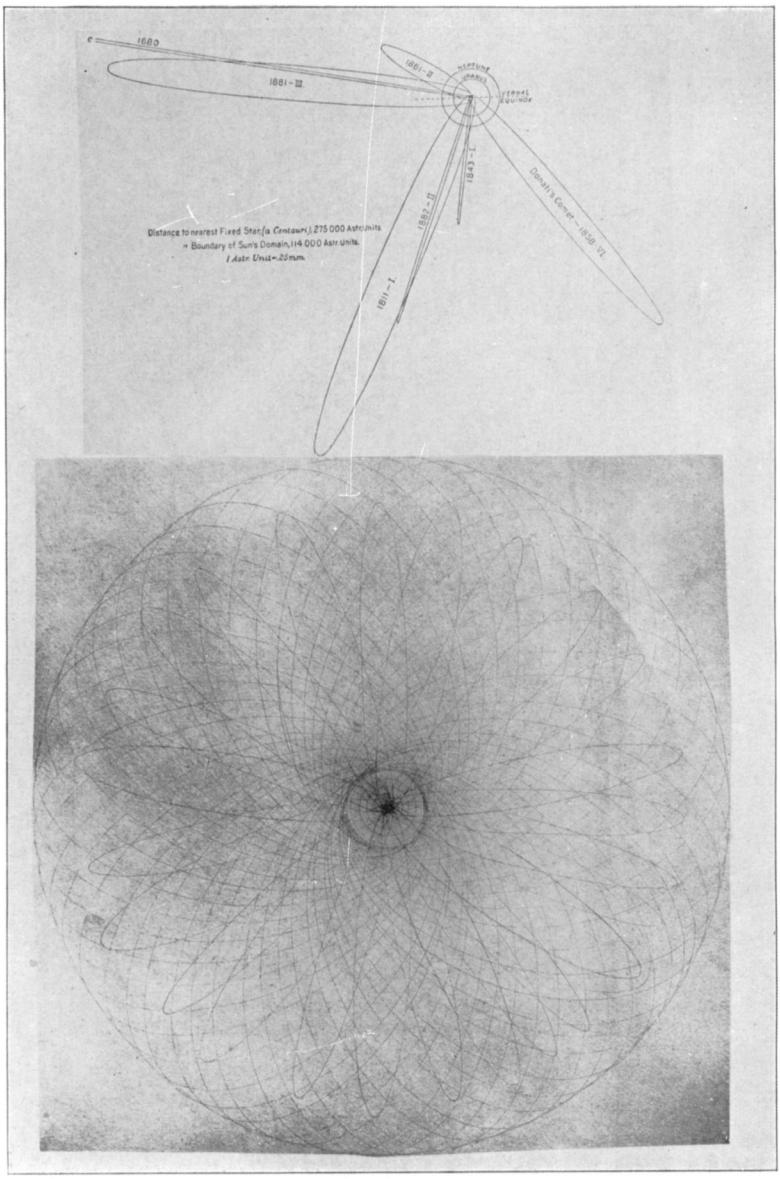
I. INTRODUCTORY REMARKS.

The comparatively recent discovery of the nature of our system of comets, and the proof of their relationship to the other classes of bodies observed in the solar system, may be considered a very notable step in astronomical progress. It will be shown below that this advance is due to several independent investigations, all tending towards a similar goal, but brought to a culmination chiefly by Fabry (1893-1904), Fayet (1897-1906), Leuschner (1907), See (1908-1910), and Strömgren (1898-1910).

The last investigation by Strömgren is the most conclusive as to the *fact of the elliptical character of the orbits of all comets,* while my own work on the nature of our system of comets and on the origin of the solar system furnishes the most satisfactory reason *why the orbits of the comets are elliptical.* Thus the one investigation establishes the *fact,* the other explains the *cause* of the arrangement observed in nature; and the two investigations, following the earlier work above mentioned, supplement each other in a highly satisfactory manner.

It is justly remarked that for many centuries the unexpected coming and going of comets, with the wonderful variety and the strange aspect of their tails, has excited the curiosity and often the terror and consternation of millions of mankind. And even at the present time the appearance of a bright comet awakens much public interest, and is duly chronicled in the press, and read by multitudes of citizens of all classes, some of whom are superstitious, but the majority probably merely curious. In the future, when a new comet appears, a part of the mystery attaching to these bodies probably will be wanting, for we seem to have good evidence that the comets are mere relics of the ancient nebula which formed our solar sys-

[1] Popular address to the Astronomical Society of the Pacific, November 25, 1911. The Publication Committee has kindly favored the author with several valuable suggestions, most of which have been adopted, but the author naturally assumes the entire responsibility for the address as now presented to the public.


1680
1861 – III
1861 – II
Neptune
Uranus
1843 – I
1882 – II
1811 – I
Donati's Comet – 1858 VI
Distance to nearest Fixed Star (a Centauri), 275 000 Astr. Units
= Boundary of Sun's Domain, 114 000 Astr. Units.
1 Astr. Unit = 25 mm.

tem, and therefore their appearance should excite no more surprise than the passing of a cloud in the sky.

Instead of the public puzzling itself over the special comet that has appeared, it ought rather to educate itself to the fact that the comet now visible is but one of an infinite multitude of small and generally invisible bodies descending to our Sun from the outer shell of the ancient neubla which formed our solar system; and that the planets, including our own Earth, have been built up by the gradual accretion of cosmical dust once existing in our nebula, in the form of wisps of nebulosity, or comets. Thus, in time both the terror and the mystery of comets will largely disappear, but the deep interest in the aspects of these bodies ought to survive and continue to sustain men of science in accumulating data for the detailed study of our whole system of comets, of which we know as yet but a very small fraction, because the vast multitude have never been seen since human history began.

As it seems to be proved that KEPLER was right in holding that there are as many comets in the heavens as there are fish in the sea, this work of investigating them will have to go on century after century, not unlike the fishing in the ocean. In this comparison the astronomer is the fisherman and the comets are the fish, and all the catches and discoveries of the astronomer, in the oceans of space, are offered to the public free of charge, notwithstanding the great sacrifice of time and effort involved in the work of sweeping the heavens throughout the night, and of investigating the orbits by the most laborious processes of observation and calculation.

II. EARLY VIEWS OF COMETS, PRIOR TO THE EPOCH OF NEWTON.

The recent establishment of the laws of the formation of the solar system marks an important epoch in modern astronomy, and opens up to our contemplation such vast domains of new thought, that it may be well to consider in some detail the problem of the comets as illustrating one of the chief results of cosmogony. Like astronomy itself, cosmogony has more than renewed its youth, and taken on such lusty vigor that it has become at once the oldest and the newest of the sciences. Such a beautiful development seems especially appropriate to the science of the invisible processes of creation. In general

these wonderful processes are withheld from the human eye, and can be revealed only to the penetrating mental vision of the geometer and natural philosopher, to whose researches we owe this sublimest portion of human knowledge.

The comets have always been regarded as the most mysterious of the heavenly bodies, not only on account of the striking physical aspects of these unexpected visitors, but also on account of the radical difference between their orbits and those of the planets. For a long time the motions of comets seemed to defy calculation; but even among the ancients there were some philosophers who declared that their apparently erratic motions eventually would be reduced to order and regularity. Thus SENECA expresses himself as follows: "The time will come when those things which are now hidden shall be brought to light by time and persevering diligence. Our posterity will wonder that we should be ignorant of what is so obvious."[1] Then he adds that the motions of the planets, though complex and seemingly confused, have been reduced to rule, and some one will come hereafter who will reveal to us the paths of the comets. In his "History of the Inductive Sciences,"[2] WHEWELL remarks that these opinions are chiefly remarkable as showing the persuasion of universal law and the belief in its ultimate discovery, which grow up in the human mind when speculative knowledge becomes a prominent object of attention. This belief in the discovery of universal law is emphasized also by the following enthusiastic praise bestowed by PLINY upon the astronomers HIPPARCHUS and THALES: "Great men! elevated above the common standard of human nature by discovering the laws which celestial occurrences obey, and by freeing the wretched mind of man from the fears which eclipses inspired,—hail to you and to your genius; interpreters of heaven, worthy recipients of the laws of the universe, authors of principles which connect gods and men!"

From these expressions of SENECA and PLINY we see that, obscure as were many celestial phenomena to the ancients, their leading philosophers were full of hope that the laws of nature eventually would be disclosed to the earnest seeker after truth; and the history of modern science confirms their anticipations.

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[1] "Quaestiones Naturales," VII, 25.

[2] Vol. I, p. 210.

In general, the ancients followed ARISTOTLE, who held that the comets are exhalations from the upper atmosphere, and thus closely connected with meteorology. Accordingly, they were ordinarily held to be within the orbit of the Moon, though ARISTOTLE had not restricted them to this region; but, on the contrary, imagined that they had some relation to the Milky Way, which was already recognized by DEMOCRITUS and ANAXAGORAS as due to the light of certain stars. In fact, ARISTOTLE believed that the exhalations noticed in the tails of the comets were identical with the milky light of the galaxy, and that both phenomena were due to vapors which tended to ignite by spontaneous combustion.

The more restricted view that the comets are within the orbit of the Moon had, however, become adopted by the Arabians during the Middle Ages, and it prevailed among Europeans prior to the time of TYCHO BRAHÉ. The great Danish astronomer soon proved by simultaneous observations on the comet of 1577, taken at Uranibourg and at Prague, that comets show no sensible parallax, and must therefore be beyond the orbit of the Moon, and thus true celestial bodies like the planets. Unable, however, to break away entirely from the traditions of the Greeks, TYCHO contented himself with the view that the comets, like the planets, probably revolve in circles, though it was impossible to explain their apparent motions on this hypothesis.

KEPLER made a better approximation to the true paths when he conjectured that the comets move in straight lines; for both the geocentric and heliocentric motions often are roughly rectilinear for considerable periods, but never for an entire revolution of a comet in its orbit.

It seems to have been first remarked by HEVELIUS in 1668 that the orbits of comets are curved near perihelion, with the concave side towards the Sun; and he even suggested that the curve might be a parabola, but did not assert that the Sun would be in the focus. Shortly afterward BORELLI went a little further and concluded that the orbit of a comet might be either a parabola or an ellipse. This was about a decade before the establishment of the theory of universal gravitation by NEWTON, who often quotes the views of his predecessors.

In 1681 DÖRFEL, of Upper Saxony, made a careful study of the motion of the great comet of 1680, and proved by graphical and other methods of calculation that the path was a parabola, with the Sun in the focus.

III. VIEWS OF NEWTON.

We shall quote these views with some care, because it does not seem to be generally known that NEWTON held that the orbits of comets always are ellipses, but with such high eccentricities that in the neighborhood of perihelion they are easily confused with parabolas. NEWTON says:—

"Hence, also, it is evident that the celestial spaces are void of resistance. For though the comets are carried in oblique paths, and sometimes contrary to the course of the planets, yet they move every way with the greatest freedom, and preserve their motions for an exceeding long time, even where contrary to the course of the planets. I am out in my judgment, if they are not a sort of planet revolving in orbits returning into themselves with perpetual motion."[1]

After treating of Halley's Comet and deducing the time of revolution to be about 75 years, and the semi-axis major of the orbit to be about 35, NEWTON continues:—

"The other comets seem to ascend to greater heights, and to require a longer time to perform their revolutions. But because of the great number of comets and of the great distance of their aphelions from the Sun, and of the slowness of their motions in the aphelions, they will exert no inconsiderable mutual perturbations upon one another, and their eccentricities and times of revolution will sometimes be augmented a little and then again diminished. Whence it is not to be expected that comets will return in the same orbits and with exactly the same periodic times. It suffices if larger changes are not observed than those due to the predicted cause. And hence a reason may be assigned why comets are not comprehended within the limits of a zodiac as the planets are; but, being confined to no bounds, are with various motions dispersed all over the heavens; namely, to this purpose, that in their aphelions, where their motions are exceedingly slow, receding to greater distances from one another, they may suffer

[1] *Principia*, Lib. III, Prop. XXXIX, Lemma VI, Cor. 3.

less disturbances from their mutual gravitations. And hence it is that the comets which descend the lowest and therefore move the slowest in their aphelions, ought also to ascend the highest.

"The comet which appeared in the year 1680 was in its perihelion less distant from the Sun than by a sixth part of the Sun's diameter; and because of its extreme velocity in that proximity to the Sun, and some density of the Sun's atmosphere, it must have suffered some resistance and retardation; and therefore, being attracted something nearer to the Sun in every revolution, will at last fall down upon the body of the Sun. Nay, in its aphelion, where it moves the slowest, it may sometimes happen to be yet further retarded by the attractions of other comets, and in consequence of this retardation descend to the Sun. So fixed stars that have been gradually wasted by the light and vapors emitted from them for a long time, may be recruited by comets that fall upon them; and from this fresh supply of new fuel, those old stars, acquiring new splendor, may pass for new stars. Of this kind are such fixed stars as appear on a sudden and shine with a wonderful brightness at first, and afterwards vanish by little and little. Such was that star which appeared in *Cassiopeia's* Chair in 1572."[1]

Again, in the General Scholium at the end of the *Principia,* NEWTON remarks:—

"The motions of the comets are exceeding regular, are governed by the same laws with the motions of the planets, and can by no means be accounted for by the hypothesis of vortices. For comets are carried with very eccentric motions through all parts of the heavens indifferently, with a freedom that is incompatible with the notion of a vortex. Bodies, projected in our air, suffer no resistance but from our air. Withdraw the air, as is done in Mr. BOYLE'S vacuum, and the resistance ceases. For in this void a bit of fine down and a piece of solid gold descend with equal velocity. And the parity of reason must take place in the celestial spaces above the Earth's atmosphere; in which spaces, where there is no air to resist their motions, all bodies will move with the greatest freedom; and the planets and comets will constantly pursue their revo-

[1] *Principia,* Lib. III, Prop. XLII, Prob. XXII.

lutions in orbits given in kind and position, according to the laws above explained. But though these bodies may indeed persevere in their orbits by the mere laws of gravity, yet they could by no means have at first derived the regular position of the orbits themselves from those laws.

"The six primary planets are revolved about the Sun in circles concentric with the Sun, and with motions directed towards the same parts and almost in the same plane. Ten moons are revolved about the Earth, *Jupiter* and *Saturn,* in circles concentric with them, with the same direction of motion, and nearly in the planes of the orbits of those planets. But it is not to be conceived that mere mechanical causes could give birth to so many regular motions, since the comets range over all parts of the heavens, in very eccentric orbits. For by that kind of motion they pass easily through the orbs of the planets, and with great rapidity; and in their aphelions, where they move the slowest, and are detained the longest, they recede to the greatest distances from each other, and thence suffer the least disturbance from their mutual attractions. This most beautiful system of the Sun, planets and comets could only proceed from the counsel and dominion of an Intelligent and Powerful Being. And if the fixed stars are the centers of other like systems, these being formed by the like wise counsel, must be all subject to the dominion of One; especially, since the light of the fixed stars is of the same nature with the light of the Sun, and from every system light passes into all the other systems. And lest the systems of the fixed stars should, by their gravity, fall on each other mutually, He hath placed those systems at immense distances one from another."

These remarkable passages show that NEWTON regarded the comets as a sort of planet ranging freely over all parts of the heavens; and whilst he held firmly to their return in elliptic paths of high eccentricity, he was quite unable to explain how they were set revolving in their orbits.

In his "History of Physical Astronomy,"[1] GRANT says:

"The question with respect to the end which comets are designed to serve in the economy of creation appears to be involved in a degree of obscurity greater even than that

[1] London, 1852, p. 315.

which surrounds any other inquiry connected with these mysterious bodies."

On this point NEWTON expresses himself as follows:—

"The tails therefore that rise in the perihelion positions of comets will go along with their heads into the remote parts, and together with the heads will either return again from thence to us, after a long course of years; or, rather, will be rarefied, and by degrees quite vanish away. For afterwards in the descent of the heads towards the Sun, new short tails will be emitted from the heads with a slow motion; and those tails by degrees will be augmented immensely, especially in such comets as in their perihelion distances descend as low as the Sun's atmosphere. For all vapor in those free spaces is in a perpetual state of rarefaction and dilatation. And from hence it is, that the tails of all comets are broader at their upper extremity than near their heads. And it is not unlikely but that the vapor, thus perpetually rarefied and dilated, may be at last dissipated and scattered through the whole heavens, and by little and little be attracted towards the planets by its gravity, and mixed with their atmosphere. For as the seas are absolutely necessary to the constitution of our Earth, that from them the Sun, by its heat, may exhale a sufficient quantity of vapors, which being gathered together into clouds, may drop down in rain, for watering of the Earth, and for the production and nourishment of vegetables; or being condensed with cold on the tops of mountains (as some philosophers with reason judge) may run down in springs and rivers; so comets seem to be required, that from their exhalations and vapors condensed, the wastes of the planetary fluids, spent upon vegetation and putrefaction, and converted into dry earth, may continually be supplied and made up."[1]

In this last hint NEWTON comes quite near to our modern idea that the planets are built up from cosmical dust resulting from the disintegration and destruction of comets.

Having established the law of universal gravitation and shown that a body may move about the Sun in an ellipse, parabola, or hyperbola, the form of curve depending on the initial velocity with which it is started, NEWTON left to his successors the development of the theory of comets. By the

[1] *Principia,* Lib. III, Prop. XLI, Prob. XXI, near the close.

discussions of the motion of particular comets, such as that of 1680, however, he showed that the orbit is sensibly parabolic, and that the radii vectores drawn to the Sun, supposed to be in the focus, describe equal areas in equal times. He recommended that search be made for the periodic comets by finding orbits having identical positions in space, with comets returning at equal or nearly equal intervals of time.

This last suggestion led to the cometary researches of the celebrated Dr. EDMUND HALLEY, including the detection of the famous comet which bears his name. Having collected all the recorded observations on comets which could lay claim to much accuracy, HALLEY developed NEWTON'S method for calculating orbits, and by incredible labor at length succeeded in computing the orbits of twenty-four comets. Three among these appeared to be the same body returning at intervals of about seventy-five years, the previous apparitions having been noted by APPIAN in 1531, by KEPLER in 1607, and the last by HALLEY himself in 1682. This led to HALLEY'S recognition of the first periodic comet, and the prediction of its return in 1758.

The periodicity of one comet being thus established by observation and gravitational theory, the list of such bodies was in time considerably extended, at first slowly, but in recent times much more rapidly.

Thus LEXELL'S periodic comet dates from 1770, ENCKE'S from 1818, BIELA'S from 1826, FAYE'S from 1843, and so on. The difficulties in proving that the orbits are elliptic are of two kinds:—

(1) *Observational difficulties,* due to the fact that in early days faint comets often escaped notice entirely, owing to the inferiority of the telescopes then in use, and the paucity of observers; or when the comets actually were observed, they were followed for such short intervals of time that only the paths in the region of the perihelion could be observed, and it was not possible to discriminate between a long narrow ellipse and a parabola, and the latter curve therefore usually was preferred for reasons of simplicity in calculation.

(2) *Analytical difficulties,* due to the fact that the elliptic orbit has two more elements to determine than the parabola,

eccentricity, major axis; and as the orbits of comets have always been difficult of calculation, prior to the development of LEUSCHNER'S Short Method a few years ago, it was natural for calculators to prefer the simplicity of the parabolic orbit and be content with it, unless the observations gave decided evidence of an elliptical path, which was seldom the case.

The hypothesis of parabolic motion usually sufficed to represent the observations with moderate accuracy, and the discrepancies encountered were otherwise explained.

IV. VIEWS OF LAPLACE.

There came to be also a speculative reason why the parabolic orbit for comets was generally adopted by astronomers. It happened that after his great work on the "Mechanics of the Solar System," LAPLACE proposed the nebular hypothesis in 1796, and accounted for the remarkable roundness of the orbits of the planets and satellites by the throwing off of rings of vapor, which was held, had afterwards condensed into the bodies now observed in our system. In this hypothesis the comets, owing to their extraordinarily high eccentricities and various inclinations, were pronounced strangers to the planetary system; and, as LAPLACE'S views were generally accepted, it was supposed that the comets should naturally move in parabolic orbits, so that simplicity in theory and calculation was imagined to rest on a physical basis founded in the accepted theory of cosmogony.

From all these various circumstances, the true theory of comets was very difficult to arrive at. For, although NEWTON held the elliptic theory of the orbits of comets, it could not be proved in his time, except in the one case of HALLEY'S Comet, while the rest might be parabolic. Later on another such elliptic orbit was found for LEXELL'S Comet of 1770, but before others were established LAPLACE'S views on cosmogony had become dominant, and the comets were believed to be visitors to the solar system from the regions of the fixed stars. The method for calculating orbits developed by OLBERS in 1798, presupposed parabolic motion, and the same theory was

accepted in the works of GAUSS. All the older works on orbits, chiefly for simplicity in treatment,[1] rested on the parabolic hypothesis, and by long usage it became so thoroughly established in scientific literature that LEUSCHNER and other recent investigators have experienced some difficulty in overthrowing it. The problem, however, has recently been attacked from independent points of view by four investigators, and the outcome of their work shows that the orbits of comets certainly are ellipses, as originally conjectured by NEWTON.

We shall now give a brief account of these recent researches by FAYET, LEUSCHNER, SEE, and STRÖMGREN, and show in what way they are conclusive against the parabolic theory, which has obstructed our progress for over two centuries. As the results now reached seem to be final, it appears to be advisable to treat this important subject in some detail.

In the development of the true modern theory that the comets belong to our solar system, three early investigators should be especially mentioned—namely, FABRY (1893-1904), FAYET (1897-1906), and STRÖMGREN (1898-1910). The work of FAYET in part preceded that of STRÖMGREN, but the latter's work in 1910 was the final culmination of these efforts, and gave us the first definite proof, for the critical cases of supposed hyperbolic motion, that all the comets move in ellipses. The work of FAYET must justly be considered the greatest single contribution to the problem of determining the original eccentricities with which comets have entered our field of observation. It was FAYET'S early work which led STRÖMGREN to improve the methods more and more, as a result of criticism by FABRY[2] and others.

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[1] GAUSS states explicitly, in the introduction to the Theoria Motus, that the problem gained great simplicity by the assumption of parabolic motion, and as to the parabola as a universal form of orbit he definitely states (Præfatio, p. v): "Haud equidem aderat ratio sufficiens, cur cometarum traiectoriæ absoluta præcisione parabolicæ præsumerentur: quin potius infinite parum probabile censeri debet, rerum naturæ unquam tali suppositione annuisse." OLBERS likewise states: "Wenn die Cometen gleich nie Parabeln um die Sonne beschreiben, so weiss man doch, dass man die kleine Stück ihrer elliptischen Bahn, das in der Nähe der Sonne liegt, und worin sie uns sichtbar sind, ohne Bedenken mit einer Parabel verwechseln kann."

[2] Comptes Rendus, February, 1904.

V. RESEARCHES OF LEUSCHNER, 1907.

For several years prior to 1907 Professor A. O. LEUSCHNER of the University of California was occupied with a preliminary statistical study of the orbits of comets, and especially of their probable eccentricities. His report on this work is printed in the *Publications* of the Astronomical Society of the Pacific for April 10, 1907, and gives his methods and results in condensed form. It is sufficient to say that he studied the orbits of comets from two points of view—(1) the average form of the orbit taken over fifty-year periods beginning with 1755; (2) the duration of visibility in days. Where the arc is extensive or the duration of visibility long, a strong tendency was found towards elliptic orbits; and as modern observers are able to follow comets further than the older observers, there was found also an increasing tendency to ellipses among the more modern orbits, simply because the observations are more complete and satisfactory.

LEUSCHNER says that the data he deduced "show that the longer a comet is under observation the more probable it becomes that its orbit cannot be satisfied by a parabola." He remarks that the average heliocentric arc would be the best criterion for judging of the tendency among the orbits, but as these data were not immediately available, he relied on the period of visibility in days, as most nearly corresponding to the average heliocentric arc. His Table II shows the following striking facts:—

Duration of Visibility.	e = 1
1- 99 days	68 per cent
100-239 days	55 per cent
240-511 days	13 per cent

From these results and other considerations LEUSCHNER justly inferred that "few, if any, orbits are strictly parabolas." "It is therefore extremely doubtful whether a parabola is definitely established for any comet having remained visible two hundred and forty days or more. . . . The theory that, in general, comets are permanent members of our solar system, seems to have been greatly strengthened by the foregoing preliminary statistics."

It is difficult to overrate the importance of this inquiry, and it suffices to say that it has contributed to the completion of our modern theory of the orbits of comets. After the publication of LEUSCHNER'S paper the subject was still further examined by several astronomers in Europe, but more especially by Professor ELIS STRÖMGREN of Copenhagen, whose researches will be discussed later.

VI. SEE'S RESEARCHES IN COSMOGONY, 1908.

I must now interrupt our discussion of purely cometary problems, to summarize my recent researches in cosmogony, and the bearing of these investigations on the cosmogony of comets, which is the subject of this address.

Early in 1908 I entered upon a determined effort to solve the great outstanding problem of the cosmogony of the solar system, and if possible bring the results into harmony with the spiral form of the nebulæ observed to prevail very generally throughout the sidereal universe. It is well known that what is called the Capture Theory was the result of this very extensive inquiry. By exact methods deduced from BABINET'S criterion, based on the mechanical principle of the conservation of areas, it was proved that the planets had never been thrown off from the Sun, as held by LAPLACE; but, on the contrary, that their nuclei had been formed at a great distance from the Sun, and as the masses had been built up by the gathering together of cosmical dust, the orbits had been enormously reduced in size, and the eccentricities practically obliterated by moving in a resisting medium of meteorites, comets and asteroids and similar small bodies.

Out of the infinite multitude of small bodies originally constituting our nebula, only those survived which moved in stable orbits, the rest having been absorbed and consolidated with the larger masses, as the planets and the Sun. The satellites were all captured by the planets, and even our Moon was shown to have been captured by the Earth. In the *Monthly Notices* of the Royal Astronomical Society for March, 1911, page 453, Professor E. W. BROWN of Yale University has confirmed the capture of satellites, in the process of the transfer of asteroids over *Jupiter's* orbit, by an extension of the method of three bodies which I used in treating this problem

two years ago. It is thus established that the satellites were added onto the planets, and the planets added onto the Sun, not thrown off as long erroneously believed by the followers of LAPLACE—*and this addition from without is what is meant by the Capture Theory. Accordingly, it follows that the planets and satellites were formed in our nebula, but never were any part of the central Sun.*

As it was shown that the planetary nuclei were originally small bodies revolving at a great distance from the Sun, a direct connection was thereby established with the present "home" of the comets, in the outer shell of our ancient nebula. In fact, the Sun and planets have been built up mainly by the destruction of comets, asteroids and similar small bodies; and the resistance caused by collision with such masses has indented the face of the Moon, and given rise to immense craters due to impact, while throughout the solar system it has reduced the size of the orbits and rendered them so round that PLATO, ARISTOTLE, ARISTARCHUS and other Greek philosophers believed the paths to be exact circles, preferred by the Deity, for the motions of the heavenly bodies, because the ancient geometers held that the circle is a perfect figure.

Many of the asteriods have been destroyed and many thrown within *Jupiter's* orbit, while great numbers of comets have been absorbed and captured by each planet. The planets have been built up by the downfall of cosmical dust upon their surfaces, and in the case of the Earth this layer of dust, if not eroded away by meteorological agencies, would accumulate to the thickness of a millimeter in a century. The meteors are nearly one hundred times more numerous than we formerly believed, as proved by my observations at the Lowell Observatory in 1898. The 1,200,000,000 meteors observed to be swept up by the Earth daily have their origin in the ancient nebula out of which our system was formed. The comets are simply the more conspicuous swarms of these masses, rendered striking by the long brilliant tails developed under the action of the Sun's repulsive forces while passing perihelion. The simple meaning of the comets, therefore, is that the outer shell of our ancient nebula still survives, and continually adds to the masses of the planets by meteoric showers of cosmical dust.

For it seems to be proved in my "Researches," Vol. II, that the ring nebulæ are special cases of spiral nebulæ; in some cases the arms of the spiral wind around to form a more or less perfect ring. In all these nebulæ, just as in the solar system, the smaller masses of nebulosity work from the outside towards the center; but the comets in the outer shell are diffused through such a vast spherical space that they revolve in immense periods. And as they therefore seldom pass near the central sun and disturbing planets they may long survive and give us a comet-dropping envelope, just such as the so-called "home" of the comets is observed to be. When, therefore, the original nebula has greatly shrunk up in volume, and most of the matter in the spirals or ring has gone into the central sun and planets, the outer shell still remains of immense extent; and, moreover, the comets, as wisps of nebulosity resulting from a cosmical cloud which never was very oblate, naturally appear from the center to be somewhat equably diffused over the whole sphere, as in the outer shell of a planetary nebula. These results follow from known mechanical laws, and may be said to be confirmed by the various types of nebula observed in the sidereal heavens by Sir WILLIAM HERSCHEL and more modern explorers.

Accordingly, it follows from these researches in cosmogony not only that our planets are built up by the destruction of wisps of nebulosity which we now identify with the comets, but that the process is still going on; and the indications are that the outer shell of our ancient nebula was of approximately the same size as the other vast nebula observed in the sky. It must be remembered that we are still in a nebula, although it has become so excessively tenuous as to be invisible.[1] The present radius of our nebula would seem to be at least ten thousand radii of the Earth's orbit, and maybe fifty thousand, or even one hundred thousand. For the sphere of the Sun's attraction extends almost half way to *Alpha Centauri,* the distance of which is 275,000 radii of the Earth's orbit.

These researches in cosmogony have thus given a sound physical basis for the modern theory of comets, and we find that practically all of them should revolve in elliptic orbits,

[1] The cometary envelopes about the other stars likewise seem to be invisible. A nebula has to give considerable light before we can see or even photograph it.

as found by the recent researches of FABRY, FAYET, LEUSCHNER and STRÖMGREN, and originally surmised by NEWTON long before cosmogony had begun to be developed into a science.

In order, however, to complete the argument confirming this conclusion, we must now treat of STRÖMGREN'S researches on the supposed hyperbolic comets, which were believed to point to the origin of the comets from interstellar space.

VII. RESEARCHES OF STRÖMGREN, 1910.

In the *Vierteljahrschrift der Astronomischen Gesellschaft,* Heft IV, 1910, Professor ELIS STRÖMGREN, director of the Royal Observatory of Copenhagen, gives an interesting summary of his researches on those comets which were long believed to have hyperbolic orbits, with the result of proving that the hyperbolic motion in every case is doubtful, and that further researches will probably show all the orbits to be ellipses. In order to investigate this problem in a satisfactory way, it was found necessary to re-discuss the older observations with modern data for the star places, and also to calculate the perturbations due to the larger planets, so as to find the eccentricity of the orbit on which the comet entered our solar system.

This line of inquiry was first extended to Comet 1886 II by the German computer THRAEN, in 1894, who found that the further back he carried the calculations the smaller the hyperbolic eccentricity became, so that at the epoch 1882, October 5, about 3.5 years before perihelion passage (May 3, 1886), the eccentricity was only 1.000002. As the eccentricity had diminished to this value from 1.000229, December 5, 1885, it appeared to be certain that it would sink below unity if the perturbations were carried far enough back in time. Thus he practicaly did away with the supposed hyperbolic comet of 1886, and STRÖMGREN has since confirmed the conclusion that the orbit is elliptical.

STRÖMGREN carried through a similar investigation for Comet 1890 II. On noticing that the perturbations led to a value still slightly above unity, as he went backward in time, he reinvestigated the theoretical aspects of the problem, and

in *Astronomische Nachrichten,* 4033-34, July 1905, derived an important equation of great simplicity and rigor, by which a calculator may obtain the integrated maximum effect on the semi-axis major, and hence on the eccentricity, of all perturbations prior to a given date. In practice this date must be so chosen that the radius vector of the comet at the epoch in question considerably exceeds that of the disturbing planet; and back of this epoch the ordinary method of perturbations must be applied, or some form of abbreviation, such as Dr. COWELL and Dr. CROMMELIN employed on HALLEY'S Comet during its recent visit.

STRÖMGREN was preceded in some of his researches by the French astronomer FAYET, of the Paris Observatory, who published in 1906 an important work entitled "Recherches Concernant les Excentricites des Cométés." In this work FAYET found only five comets which appeared to be hyperbolic, —namely, 1844 III, 1863 VI, 1890 II, 1898 VII, and 1899 I,— all of the rest being originally elliptic. By the further researches of STRÖMGREN and others, all these were excluded as having probable errors greater than the hyperbolic part of the eccentricity, except Comet 1898 VII, which gave an eccentricity $e = 1.0000893 \pm 0.0000165$. And now, wonderful to relate, by his latest investigations made in Copenhagen, STRÖMGREN and BRAAE have proved that also in the case of 1898 VII the supposed hyperbolic eccentricity, on strict calculation, comes within the margin of the uncertainty of this element. So that even in this extreme case the supposed hyperbolic eccentricity totally disappears.

Accordingly STRÖMGREN *justly concludes, from his extensive and critical investigations of the orbits of the supposed hyperbolic comets, that if we consider only Newtonian gravitation, and introduce no other forces, we shall probably be led to elliptic orbits in the case of every known comet.* The importance of this conclusion for the cosmogony of comets is apparent. It shows that they are original members of the solar system, as was long ago surmised by NEWTON, and that not one of them has come to us direct from interstellar space. The theory, therefore, that the comets are strangers to our solar system, as long taught by LAPLACE and generally believed by astronomers during the past century, is now abandoned.

VIII. THE CONCLUSIONS OF FAYET, LEUSCHNER, SEE AND STRÖMGREN CONFIRM THE ELLIPTICAL THEORY OF NEWTON.

To sum up these results briefly, it suffices to remark that by the important researches of FAYET in 1906, LEUSCHNER in 1907, and STRÖMGREN in 1910, we have satisfactory observational and theoretical evidence that the orbits of comets are all elliptic, the parabolic and hyperbolic orbits being now definitely and finally excluded. This is simply a fact of observation and mathematical calculation, without regard to any theory of the cosmogony of the comets. The comets, therefore, are regular members of our solar system, as originally held by NEWTON.

My own researches on the formation of the solar system,—showing that the nuclei of the planets originally revolved at great distances from the Sun, and have since been built up by the gathering together of meteorites, comets and other nebulous matter, as their orbits have been reduced in size and rounded up into almost perfect circles, the inner parts of our nebula being thus cleared of nebulosity by the formation of the Sun and planets, while the outer shell is still filled with minute wisps,—give us the physical basis of the true theory of comets. They can be nothing else than survivals of nebulosity from the outer shell of our ancient nebula, which at length has become so rare that it does not sensibly intercept the light of the fixed stars.

In the passage above cited NEWTON remarked that, while gravity could maintain, mere mechanical causes could not have established, the regular motions of the planets and satellites, and at the same time the discordant system of comets dispersed all over the heavens and moving in all directions around the Sun. But if NEWTON had conceived of an immense spiral nebula formed from dust expelled from the stars, and necessarily taking, as it gathered together, a form sufficiently unsymmetrical that it would gradually settle and assume a slow rotation about an axis, he would have seen that the resulting development would account for both planets and comets, and all the order and design which he saw in the wonderful arrangement of our solar system.

Having thus reached what appears to be the law of nature, we believe that no one hereafter will consider the abandoned

doctrines that the planets and satellites were thrown off by rotation, and that the comets came to us direct from the fixed stars. On the contrary, the comets will be viewed in their true light as the surviving residue of our ancient nebula and a part of the regular order of our development from a nebula of vast extent, the particles of which were originally expelled from the stars in the great stratum of the Milky Way and therefore gathered originally from all directions in space. Thus the beautiful and mysterious system of comets so widely diffused about our Sun, moving in all directions, and receding to such immense distances that we have observed but a small fraction of them since history began, is naturally explained. Moreover, it confirms the sagacious conjecture of KEPLER that there are as many comets in the heavens as there are fish in the sea. *And obviously it follows that the other fixed stars likewise have systems of planets, satellites, and comets, so that our Sun is a typical star of the Milky Way.* For the other fixed stars, having likewise developed from nebula, for similar reasons, have planets revolving in nearly circular orbits and rotating on their axes, and therefore in many cases doubtless are habitable and inhabited. About these remote suns in other regions of space great comets probably are coming and going in very elongated orbits, as actually witnessed in our solar system. Accordingly, that which for long ages was a source of terror to mortals, owing to the striking character of the comet tails developed under the action of the Sun's repulsive forces, and the unexpected apparition of these mysterious bodies, will in the future become a source of pleasure and intellectual profit.

IX. FORMATION IN THE DISTANCE UNDER THE DISTRIBUTIVE EFFECTS OF REPULSIVE FORCES AND GATHERING TOWARDS THE CENTER UNDER GRAVITATION A GENERAL LAW OF NATURE, AND ILLUSTRATED IN OUR SOLAR SYSTEM BY THE COMETS.

In an address on "The Evolution of the Starry Heavens," delivered to the California Academy of Sciences, August 7th, and published in *Popular Astronomy* for November and December, 1911, I have pointed out that the great law of nature governing the evolution of worlds consists in the expulsion

of dust from the stars by the action of repulsive forces and its subsequent collection into clouds for the formation of nebula. The nebula thus produced will generally be of unsymmetrical figure, and in settling to equilibrium will often take the spiral form. And, moreover, in such a cosmical cloud the large bodies will work towards the center, while the smaller ones will be destroyed to furnish material for the large ones. Everywhere in nature the large bodies of the type of planets and satellites, drift towards the most powerful centers of attraction, as an inevitable effect of universal gravitation, while only fine dust is thrown off and driven away by the action of repulsive forces emanating from the central stars of the various systems.

This law of aggregation towards centers is illustrated by the globular figures of the clusters as well as by the round figures of many planetary nebulæ, and was long ago noticed by the incomparable Sir WILLIAM HERSCHEL. This clustering power was thus found to be operating throughout the sidereal universe, and HERSCHEL believed that it is gradually breaking up the Milky Way into a series of star-clouds, and thus already presents the aspect of a clustering stream, rather than a uniform band of Milky Light. But if the new theory be true, that in the long run a balance is preserved between the attractive and repulsive forces of nature, the aggregation in great centers of attraction being counterbalanced by the expulsion of fine dust from the stars and the formation of nebula in the vacant regions of space, then it will follow, as I have pointed out in my "Researches," Vol. II, that the breaking up of the Milky Way is finally counteracted by a dispersive tendency, and does not proceed so far as HERSCHEL supposed.

X. PROJECTILE MOTIONS INDICATE FORMATION IN THE DISTANCE.

Sir WILLIAM HERSCHEL observed that the stellar systems have been endowed with projectile motions which preserve them for millions of ages.[1] These projectile forces imply the gathering of matter from a distance, in the same way by which I have explained the origin of the spiral nebula. And the fact

[1] *Phil. Trans.*, 1785, p. 217.

that the breaking up of the Milky Way is not more pronounced than it is, after the lapse of such immeasurable time, may be regarded as nature's indication that a counteracting or preservative tendency is at work in the sidereal universe. This process of restoration depends on the action of repulsive forces which counteract the ravages of universal gravitation, through the dispersion of dust from the stars.

Now of the gathering of cosmical dust from the distance our system of comets affords tangible proof, since this is the only way in which such an equably diffused system could have been started. In pondering over this fact, Sir ISAAC NEWTON justly remarked *that while gravity would explain the movement, it could not assign the cause why these bodies were set revolving in orbits diffused indifferently over all parts of the heavens.* The introduction of the doctrine of repulsive forces is of use, therefore, not only in the theory of the tails of comets, but also in the theory of the arrangement of their orbits in space.

This extension of the sublime science of celestial mechanics as developed by NEWTON, with the confirmation of his theory of the elliptical orbits of comets and the establishment of the physical cause thereof, seems likely to be not the least interesting contribution of our age to the geometry of the heavens.

MARE ISLAND, CALIFORNIA, November 15, 1911.